Frameless Stereotactic Image–Guided C1–C2 Transarticular Screw Fixation for Atlantoaxial Instability

Review of 20 Patients

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Objective: We retrospectively studied 20 adults who underwent C1–C2 transarticular screw (TAS) fixation utilizing frameless stereotaxy.

Methods: The study group comprised 13 men and 7 women, with a mean age of 63 years (range 12–87 years). All patients demonstrated clinical and radiographic evidence of C1–C2 instability. The cause of the instability was trauma in 11 patients, rheumatoid arthritis in 6 patients, failed prior surgery in 2 patients, and congenital malformation in 1 patient. All patients underwent stabilization with C1–C2 TASs using image-guided frameless stereotaxy.

Results: There were no new or worsening neurologic symptoms reported at 18-month follow-up. Motor weakness improved in seven of nine patients, myelopathy in seven of seven, and gait in three of six patients in whom these deficits were present preoperatively. Postoperative complications included one surgical site abscess, one cutaneous pressure ulcer, and one iliac crest donor site infection. Of 36 screws placed, 33 (92%) were well positioned. Normal C1–C2 alignment was achieved in 17 of 20 (85%) patients. In 4 of 20 cases, screw implant, which was thought to be anatomically difficult, if not impossible, on the basis of routine magnetic resonance or computed tomography imaging, was actually accomplished successfully using surgical navigation.

Conclusions: C1–C2 TAS placement is a safe and accurate surgical technique that may improve neurologic function. Use of intraoperative navigation can facilitate achieving difficult surgical trajectories that match the patient's anatomy, thus allowing TAS implant in patients who otherwise would not be candidates for this type of internal fixation.

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Atlantoaxial instability can result from trauma, rheumatoid arthritis, congenital malformation, or tumor invasion. The goal of treatment is stabilization of the C1–C2 complex to prevent neurologic and neurovascular compromise. First described in 1987 by Magerl and Seemann, C1–C2 transarticular screw fixation has been shown to yield excellent fusion rates.[1–4] Several authors have reported that this technique offers the best biomechanical stability and allows the least amount of rotation.[5–8] However, placement of transarticular screws (TASs) is technically challenging and incurs significant risk of neural and vascular injury. Previous clinical studies of C1–C2 TAS fixation have reported screw misplacement in up to 15% of patients, with an 8% rate of vertebral artery (VA) injury.[9,10] Safe and accurate screw placement requires thorough radiologic assessment of the cervical spine with careful preoperative planning of screw trajectory.[11–13]

For years, lateral fluoroscopy has been used to guide TAS placement.[14] This imaging modality, however, is limited in that it provides only a one-dimensional representation of the C1–C2 complex, thus rendering accurate screw placement difficult. To correct this shortcoming, several authors have expanded on fluoroscopic guidance and now use biplanar fluoroscopy, which provides a two-dimensional image set of the C1–C2 segment, therefore improving the accuracy of TAS placement.[15] Recently, computer-generated image guidance has been introduced as a useful adjunct to provide an even more accurate three-dimensional representation of the craniocervical junction.[15–17] Frameless stereotaxy provides preoperative planning and intraoperative visualization of the trajectory through the C2 pars while allowing navigation around potential hazards such as an anomalous VA.[16] Therefore, some authors advocate that image guidance may allow for safer and more accurate screw placement.[1,15–17]

To date, only two clinical series have reported outcomes after frameless stereotaxy-guided TAS placement.[17,18] These studies reported good screw placement in all instances with no complications. However, none reported the postoperative clinical outcomes of patients, such as improvement in neck pain or myelopathy. In this article, we not only describe the technical results such as accuracy of screw placement but also detail the clinical outcomes.

MATERIALS AND METHODS

Patient Population

Between May 1998 and May 2001, 20 patients (13 men and 7 women; mean age 63 years, range 12–87 years) underwent TAS placement utilizing frameless stereotaxy. After obtaining institutional review board approval, a retrospective chart review was performed. All patients demonstrated clinical and radiographic evidence of C1–C2 instability. The cause of the instability was trauma in 11 patients, rheumatoid arthritis in 6 patients, failed prior surgery for C1–C2 instability due to rheumatoid arthritis in 2 patients, and Chiari type 1 congenital malformation in 1 patient. Patients presented with neck pain (11/18), motor weakness (9/18), sensory symptoms (7/18), gait/coordination abnormalities (6/18), and myelopathy (7/18) (Table 1).

Preoperative Imaging

Preoperative imaging of the cervical spine included radiographs with flexion–extension films, magnetic resonance imaging, and thin-cut computed tomography (CT). In addition, the Stealth Station (Medtronic Sofamor Danek, Memphis, TN) was used to reconstruct a three-dimensional CT image of the C1–C2 complex (Fig. 1). A safe and accurate screw trajectory was then charted, using previously described guidelines.[9,12,17] The ideal trajectory allows passage of the screw through the lateral mass of C2 without breach of the cortex into the spinal canal and avoids the VA and C2 nerve root.

Surgical Technique

After satisfactory induction of general endotracheal anesthesia, patients were placed in Mayfield pins in the prone position. Lateral fluoroscopy was used to correctly position the cervical spine in anatomic alignment. A midline incision was made from C1 to C3 and taken down with Bovie electrocautery to the tips of the spinous processes. C1 and C2 were widely exposed in the subperiosteal plane. A paravertebral skin perforation was made opened in the cervicothoracic region to accept the drill guide cannulas. The Stealth reference arc was affixed to the C2 spinous process and registered. With use of lateral fluoroscopy and the Stealth Station, a fully threaded C1–C2 titanium screw was placed along the preoperatively planned trajectory (Fig. 2). This process was repeated on the opposite side. An iliac crest graft was harvested after debridement of the subchondral layer of the C1–C2 facet joint. The posterior arch was packed with the bone graft and secured by placement of a sublaminar titanium cable. The incision was then closed in layers, and a dressing was placed. Patients were placed in a cervical collar (one in a halo), turned into the supine position, and removed from the Mayfield head holder.

TABLE 1. Symptoms at Presentation of Patients With C1–C2 Instability

Symptom	No. of Patients	% With Symptom
Neck pain	11	61
Motor weakness	9	50
Sensory	7	39
Abnormal gait	6	33
Myelopathy	7	39
Total no. of patients	18	

Clinical and Radiographic Follow-Up

Outcome was recorded as "better, worse, or same" compared with the preoperative status. If a patient was free of a particular deficit preoperatively and postoperatively (eg, no neck pain), the outcome was recorded as "same." Follow-up times ranged from 1 to 18 months with a mean of 6.1 months. Two patients were lost to follow-up and were excluded from the clinical outcome analysis.

All patients had postoperative radiographs of the cervical spine (Fig. 3). In addition, we obtained postoperative CT scans in 40% (8/20) of the patients. Patients receiving postoperative CT scans were those in whom screw positioning and vertebral anatomy were unusually challenging. Radiographic outcomes such as assessment of screw placement were determined by an independent blinded neuroradiologist. To supplement postoperative imaging, the pars height and width were also measured for each patient using the Stealth Station by an independent neurosurgeon. Screw position, stability, and osseous fusion were defined as follows: (a) A screw was considered well positioned if it passed through the lateral masses of both C1 and C2 vertebrae and crossed the joint in between C1 and C2.[9] (b) A malpositioned screw was designated as too short, too long (screw protrudes >1 cm out of C1 cortex), too high, or missed the lateral mass of C1 laterally, medially, or inferiorly. (c) Fusion was considered complete if there was continuity of bone between the posterior arches of the atlas and axis and no movement was observed on flexion–extension radiographs.

RESULTS

Radiographic Evaluation

A total of 36 screws were placed in 20 patients. Four patients had only unilateral screw placement because of unsuitable foramen transversarium anatomy. The unsuitable anatomy had been determined during preoperative planning with CT and Stealth reconstruction (Fig. 4). The diameter of all screws placed was 4 mm. Left pars mean height measured 5.3 mm (range 4.0–7.2 mm) and mean width 5.7 mm (range 4.0–8.8 mm). Right pars mean height was 5.2 mm (range 3.5–7.5 mm) and mean width 5.6 mm (range 3.5–11 mm).

Postoperatively, 33 of 36 (92%) screws were well positioned. In the opinion of the operating surgeon, 8 of these 33 screws could not have been safely placed without use of intraoperative image guidance. This was due to either aberrant VA anatomy or an unusually narrow C2 pedicle diameter that would have precluded TAS placement with either lateral or

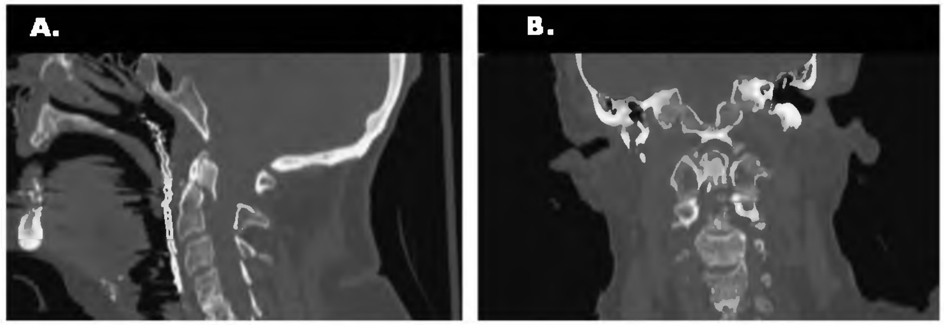

FIGURE 1. Preoperative sagittal (A) and coronal (B) CT reconstruction demonstrating a type II odontoid fracture with posterior subluxation.

biplanar fluoroscopy. The three malpositioned screws missed the lateral mass of C1: one medially, one inferiorly, and one laterally and inferiorly. There was no technical difficulty with image guidance found in these cases to explain the aberrant implant trajectory. All three patients with malpositioned screws displayed complete reduction of dislocation and did not have neural or vascular injury in conjunction with aberrant screw placement. Two of these three had osseous fusion documented at follow-up. One patient with a malpositioned screw did not have osseous fusion at the 7-month follow-up, and no patient had persistent pain and/or neurologic deficit. Of the patients with optimal screw position, 10 had a follow-up of at least 6 months, and all 10 (100%) demonstrated satisfactory fusion on plain anteroposterior and lateral radiographs. Satisfactory C1–C2 alignment, defined as a postoperative atlantodental interval of ≤2 mm, was achieved in 17 of 20 patients.

Clinical Outcomes

We analyzed the clinical outcome of 18 adult patients who underwent image-guided TAS placement (Table 2). Overall 61% (11/18) of patients reported improvement in neck pain. Motor strength and myelopathy were better in 39% (7/18). Seventeen percent (3/18) had improved coordination

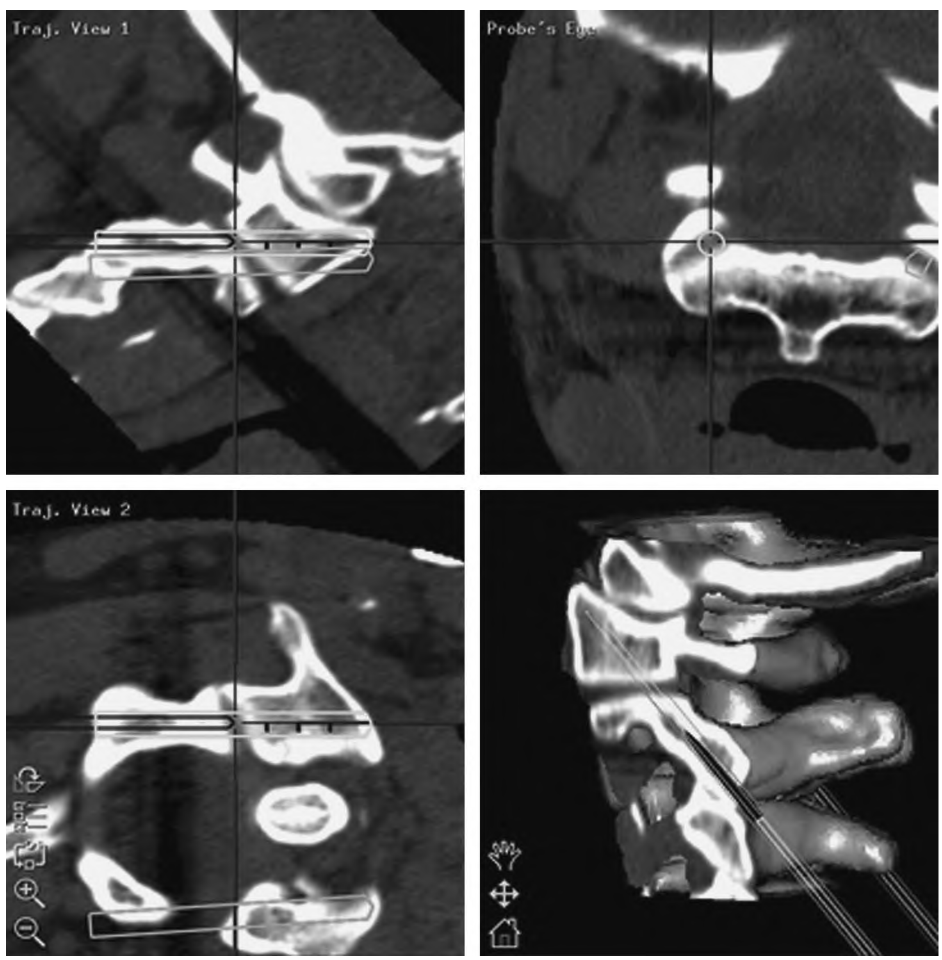

FIGURE 2. Intraoperative Stealth Station image guidance screen during placement of a left C1–C2 TAS (crosshairs). Sagittal trajectory (top left), probe's eye (top right), and axial trajectory (bottom left) views during screw placement. The planned trajectory is also shown in reference to the three-dimensional CT reconstruction through the C1–C2 complex (bottom right).

FIGURE 3. Lateral cervical radiograph demonstrating optimal position of TASs.

and gait. Postoperatively, no patients developed new symptoms or neurologic deficits. In addition, no patients had deterioration in any of their preoperative symptoms. All 11 patients with preoperative neck pain reported it to be better or resolved at follow-up (Table 3). Similarly, all seven patients with preoperative myelopathy improved. Among the nine patients with motor weakness before surgery, improvement was seen in seven (78%), and there were no cases of postoperative deterioration. Similarly, gait and coordination improved in three of six (50%) patients and were unchanged in the rest. There were no intraoperative neurovascular complications. Postoperative complications were seen in three patients including a decubitus ulcer of the scapula where the halo vest attached, an infection of the iliac graft site, and a paraspinal abscess. One reoperation was necessary to drain the paraspinal abscess. All three patients did well and were eventually discharged in good condition.

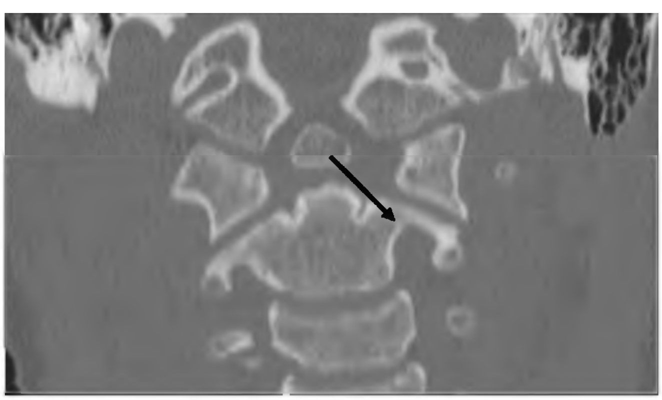

FIGURE 4. Coronal CT reformat of a patient with a type II odontoid fracture showing an enlarged left VA groove (arrow), causing erosion of the C2 lateral mass and pedicle. In this patient, TAS fixation was limited to the right side.

TABLE 2. Postoperative Results of All Patients With C1–C2 Instability (n = 18)

Symptom	Better (%)	Worse (%)	Same (%)
Neck pain	11 (61)	0 (0)	7 (39)
Motor weakness	7 (39)	1* (6)	10 (56)
Sensory†	3 (17)	0 (0)	15 (83)
Coordination/gait	3 (17)	1* (6)	14 (78)
Myelopathy	7 (39)	0 (0)	11 (61)

*This one patient had a stroke 3 months after the C1–C2 surgery, which resulted in right sided weakness. The stroke was not thought to be related to the surgery.

†Improvement in sensory symptoms is usually not stated or focused on at the postoperative evaluation; the improvement may be an underestimate.

DISCUSSION

We present the postoperative clinical outcomes of 18 patients with atlantoaxial instability who underwent image-guided C1–C2 TAS fixation. Although our average follow-up period was only 6 months, none of our patients developed new neurologic symptoms or experienced worsening of their preoperative symptoms. Neck pain and myelopathy were improved in all patients with these symptoms preoperatively. Seventy-eight percent of patients with preoperative motor deficit and 50% of patients with abnormal preoperative gait/coordination reported postoperative improvement. Prior clinical studies have reported a near 100% improvement or stabilization of neurologic status.[9,17] However, with the exception of preoperative neck pain, most studies have had a very low incidence of preoperative myelopathy and neurologic symptoms.[1,17] In contrast, almost 40% of patients in our series presented with myelopathy, indicative of a more severe clinical course. Despite this, we report a 100% improvement or stabilization of neck pain and neurologic status.

We evaluated the placement of 36 C1–C2 TASs. Only two prior studies have reported on the technical outcome of

TABLE 3. Postoperative Results of Patients With Specific Preoperative Symptoms

Symptom	No. With Preop. Symptoms	Better	Worse	Same
Neck pain	11	11 (100)	0 (0)	0 (0)
Motor weakness*	9	7 (78)	0	2 (22)
Sensory†	7	3 (43)	0	5 (57)
Coordination/gait	6	3 (50)	0	3 (50)
Myelopathy	7	7 (100)	0	0

Values in parentheses are percentages.

*Given as change from preoperative function, assessed for patients with specific preoperative symptoms only.

†Only one patient developed a new symptom (right-sided weakness after a stroke thought to be unrelated to the surgery) that was not present preoperatively.

frameless stereotaxy-guided TAS placement. Both studies reported good placement of all screws with no VA or neural injury.[17,18] Two large studies that used lateral fluoroscopy have reported 14% and 15% of screws to be malpositioned.[9,10] In our series, 33 of 36 screws (92%) were well positioned, whereas 3 of 36 screws (8%) were malpositioned. We used radiographs in all patients as an initial means to confirm screw position. These were supplemented with CT reconstructions in any case in which there was any question of inaccurate screw placement based on the initial radiographs, as has been used by others.[19] In one patient, initial radiographs appeared to show malpositioned screws; however, CT images of the same patient subsequently showed good screw position (Fig. 5). One drawback of image-guided TAS placement based on preoperatively acquired images is that the anatomic relationships may change after surgical positioning and only the C2 segment is used for navigational registration (registration of C1 is not possible). Registration of C2, however, minimizes the main risk of TAS fixation, which is injury to the vertebral artery at the C2 level,[19] and we therefore believe this limitation is acceptable.

Our patients had more preoperative neurologic symptoms and myelopathy than those in the Wigfield and Bolger study.[17] This could potentially mean that we treated more complex patients with perhaps more difficult anatomy. The three patients with malpositioned screws did not have VA or neural injury. In addition, all three had good clinical stability of the C1–C2 complex, and two of three achieved osseous fusion. Osseous fusion or stability has been described in 87–100% of patients after TAS surgery.[1,3,4,8,9,20] We were unable to assess osseous fusion appropriately in some cases owing to the relatively short follow-up of this study; however, all 10 patients with a follow-up of at least 6 months demonstrated evidence of early osseous fusion on radiographs. Injury to the VA has been reported in up to 8.2% of patients.[9] C2 nerve root paresis and hypoglossal nerve paresis have been reported in up to 2% of patients and screw breakage in up to 4% of patients. We report no such complications in our series.

Foley and Smith[16] have described frameless stereotaxy as a valuable tool for preoperative anatomic assessment and trajectory planning. It provides unique three-dimensional information about the quality of bones, the exact measurements of the bones, and the VA anatomy. Preoperative planning of a safe trajectory has been well described and hinges on anatomic factors described above. As there are no universal parameters for accurate screw placement, it is absolutely necessary to adapt specific techniques to the unique anatomy of the individual patient.[16] The thorough anatomic evaluation and three-dimensional reconstruction provided by the image guidance system allow selection of optimal screw trajectory that is individualized for each patient's unique anatomy.

Preoperative planning and three-dimensional reconstruction made possible by frameless stereotaxy have the potential to increase the safety and accuracy of TAS placement. Amiot et al have demonstrated the advantages of computer-assisted pedicle screw placement over conventional techniques.[21] In this study, 95% of pedicle screws placed with computer-assisted image guidance were correctly positioned, whereas only 85% of screws were in correct position using conventional techniques. Moreover, 7% of patients in the conventional group required reoperations for new postoperative neurologic deficits compared with 0% in the computer-assisted cohort. Frameless stereotaxy offers unique advantages beyond those afforded by lateral fluoroscopy. It allows for three-dimensional reconstruction of the C1–C2 complex and intraoperative visualization of the screw trajectory through the C2 pars. Adjustments in screw trajectory can be made preoperatively or intraoperatively to account for the unique bony and VA anatomy of each patient. This allows for a safer and more accurate screw placement in patients with suitable, borderline, or even unsuitable anatomy.

Aberrant VA anatomy has been demonstrated in 18–23% of patients, making them unsuitable for surgery.[2,8,13,21–42] In our series, 20% of patients underwent unilateral TAS placement due to aberrant anatomy. This highlights the need for careful anatomic evaluation and preoperative planning in every patient. Frameless stereotaxy allows for evaluation of the trajectory through the C2 pars such that adjustments can be made intra- or preoperatively to take into account and avoid the VA in patients with normal as well as borderline abnormal anatomy.

TAS fixation of C1–C2 has been shown to be biomechanically superior, to allow the least rotation, and to yield

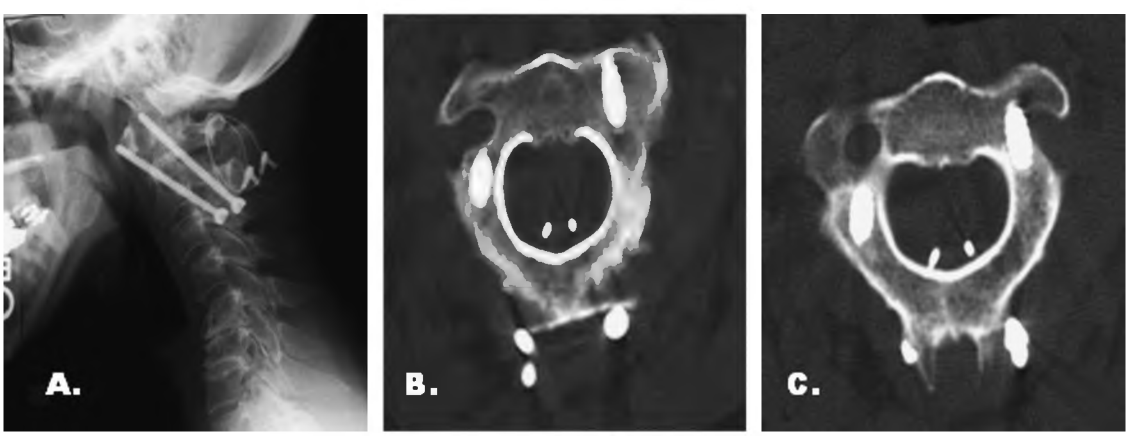

FIGURE 5. A, Postoperative radiograph showing misaligned screw. B and C, Postoperative axial CT scans of the same patient showing correct screw placement through both lateral masses.

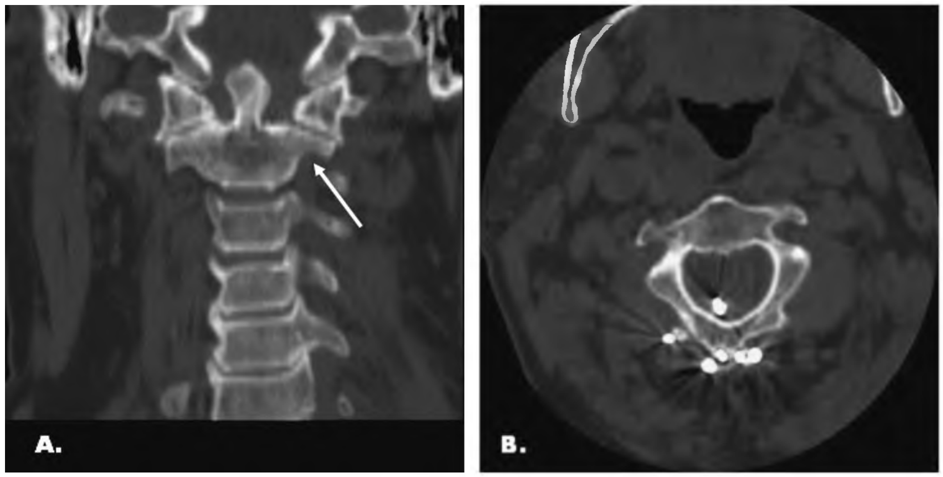

FIGURE 6. A, Coronal CT reconstruction demonstrates the asymmetry in the course of the left VA with the left C2 foramen transversarium relatively high-riding compared with the right (arrow). B, Axial CT demonstrates the relatively decreased transverse caliber of the left C2 pedicle compared with the right. Due to these anatomic findings, TAS fixation in this patient would not have been possible without image guidance.

better fusion rates than conventional fusion methods.[2,5,6,8,26,43–45] Therefore, technology that helps the surgeon place TASs in more patients with confidence has the potential to improve overall outcomes in patients in the long run. Three-dimensional frameless stereotaxy may allow TAS placement in patients deemed unsuitable for screw placement by conventional criteria.[15] In the current study, TAS placement without image guidance would not have been technically feasible in four patients with aberrant VA anatomy and asymmetric C2 pedicles (Fig. 6). These patients would therefore not be candidates for TAS fixation without image guidance. Madawi et al[9] reported incomplete reduction of C1 on C2 as being the biggest risk factor for screw malposition. As screw placement with lateral fluoroscopy uses the anterior border of C1 as the target point for screw trajectory, C1–C2 subluxation can lead to malpositioned screws and VA injury. Hence, incomplete reduction has been considered to be a relative contraindication for TAS placement. However, as C2 can be visualized in three dimensions and registered on the navigation system independent of C1, the trajectory planned with this system does not rely on the position of C1. Therefore, this technology has the potential to increase the number of patients offered this biomechanically advantageous technique of C1–C2 fixation.

CONCLUSIONS

Image-guided C1–C2 TAS placement is safe and accurate and improves neurologic status. Alignment was not optimal in 3 of 20 patients, but the goals of fixation, stabilization, and decompression were achieved. This technique can provide nonstandard surgical trajectories that match the patient's anatomy, thus allowing surgery to be performed safely in patients who otherwise would not be candidates. The learning curve for this technique is steep; however, patients will benefit in the long run as more surgeons become familiar with this technology. Finally, both radiography and CT with sagittal and coronal reconstructions should be used to determine if screw position is correct postoperatively in cases where screw placement is uncertain.

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